Seismic Response of Slender Monuments on Very Soft Soil: Case Study of a Triumph Column

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Abstract

Classical monuments are often founded upon deposits of very soft soil or upon the debris of ancient cities, the deformability of which can significantly affect their seismic response. Focusing on monuments which are prone to experiencing overturning failure, the role of soft soil on seismic performance is investigated through dynamic time history analyses using nonlinear finite elements. Inspired by "Triumph Columns", monuments of Roman origin that are widespread across the Mediterranean, the paper presents a parametric analysis of inertial loads, drift demands and permanent deformations exerted upon columns founded on idealized soil profiles of strikingly different stiffness characteristics. Ricker pulses of varying acceleration amplitudes and frequencies are used as bedrock excitations. Comparative presentation of results from 72 dynamic analyses indicates the dominating effect of soil nonlinearity. Acting as a double fuse, the latter can first attenuate the seismic motion that reaches the ground surface and then cut-off the inertial load transmitted on the superstructure. The unavoidable shortcoming is presumably associated with permanent deformations of the soil-foundation interface, especially settlements.

Keywords: monuments; seismic response; numerical analysis; finite elements.

Introduction

Monuments are unique structures with historic, cultural and emotional value. They are treated as particularly vulnerable assets, for the impact of any damage goes well beyond direct economic loss. Protection of monuments against natural hazards is crucial as well as challenging due to a multitude of factors associated with architectural characteristics, size, material ageing and uncertainties regarding construction methods of the past. Ancient Greek and Roman monuments, widespread all over the Mediterranean, are typically dominated by the presence of free-standing columns composed of drums that rest on top of each other with or without any connection. Their protection against earthquakes is critical due to the high seismicity of the area. Moreover, they are usually considered prone to overturning due to the characteristic slenderness of their structure.

A large number of past research studies have dealt with the seismic performance of classical columns assuming them as perfectly rigid (e.g., Perry 1881; Housner 1963; Psycharis and Jennings 1983; Koh et al. 1986; Psycharis 1990; Manos and Demosthenous 1992; Makris and Roussos 2000; Apostolou et al. 2007) or accounting for the presence of multiple drums (e.g., Krstevska et al. 1996; Mouzakis et al. 2002; Drosos and Anastasopoulos, 2014). Nevertheless, in their majority, these studies have considered the column being supported upon a rigid, non-compliant base. However, classical monuments are often founded on very soft soil deposits or upon the debris of ancient cities. In such case, the effect of soil response may be significant and actually twofold. First, local site conditions play a dominating role in defining critical ground motion characteristics such as the amplitude, the frequency content and the duration of the seismic motion that reaches the ground surface and excites the column. Indeed, local soil acts as a filter that refines the ground motion resulting in amplification or attenuation depending on soil dynamics and its potentially nonlinear behaviour. Additionally, introducing compliance at the base of the structure, soil deformability may lead to excessive permanent deformations, the result of hysteretic material behaviour, that may jeopardise the integrity or the serviceability of the structure.

The effect of soft soil on the seismic response of monuments can only be studied through the comprehensive prism of soil–structure interaction. Attempting a preliminary investigation, the present study has focused on a particular type of monuments: triumph columns. Originating from the Roman Empire, triumph columns are quite common in Europe and Western Asia. Due to their extreme slenderness (having breadth to height ratios of less than 0.2) they are particularly sensitive to experiencing intense rocking vibration, and possibly overturning, even for earthquake events of moderate intensity. Sliding is also a very likely mode of response in the case that the column is comprised by blocks of marble that simply lie on top of each other without being connected. Nevertheless, the response can be very detrimental when the column is founded on soft soil, due to the soil amplification of long duration excitation pulses and the increased foundation displacements.

A very characteristic case study, which highlights the key role of the soil for the response of such structures, is worth being referred to. Figure 1 shows a cross section of the Tiber valley in Rome, where two strikingly similar triumph columns, the Trajan and the Marcus Aurelius Column, lie within a distance of less than 700 m. Even so, the two columns are founded on very different soil profiles.

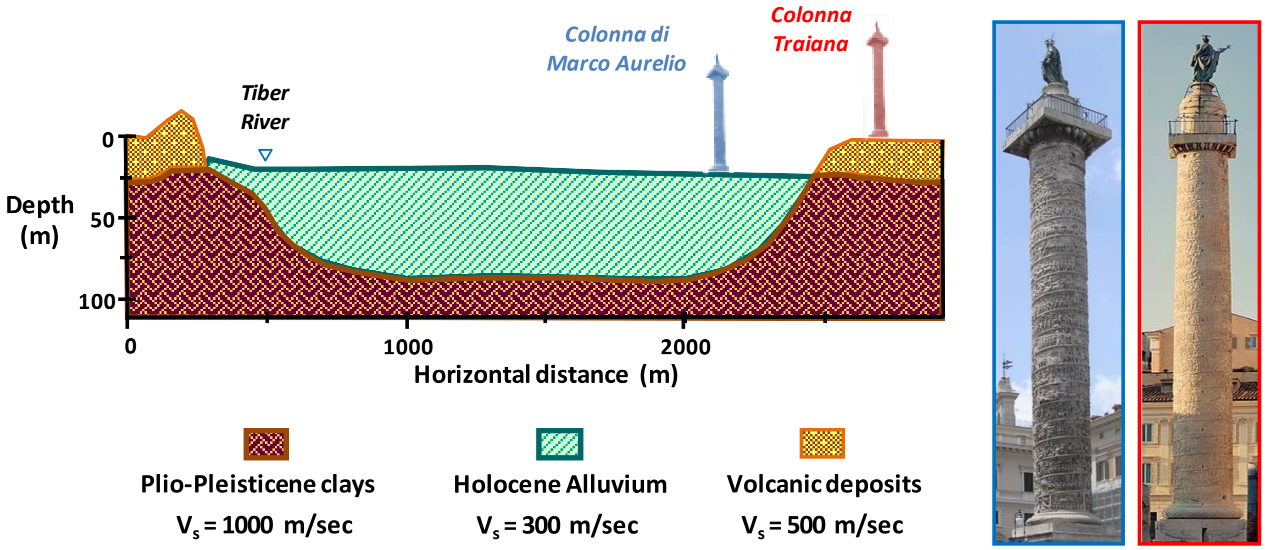

Figure 1: Section across the Tiber river valley in Rome showing the local geological setting of the sites of the Columns of Marcus Aurelius and Trajan (adopted by Boschi et al., 1995).

Standing on top of a 60 m deep soft alluvial deposit, the Marcus Aurelius Column, the structural details of which are depicted in **Fig. 2**, has suffered great damage (possibly due to past long distance earthquakes), involving significant sliding between the marble blocks (**Fig. 2a**), and is known to have been subjected to a number of restorations in the past. By contrast, the "twin" column of Trajan, which is supported on a shallower and much harder volcanic deposit, is much better preserved. Evidently, the significant difference in the performance of the two columns can be related to the following two factors: (i) standing upon soil profiles of very different dynamic characteristics, the two columns are certainly subjected to different surface ground motions; (ii) the seismic motion at the site of Marcus Aurelius is likely to have been significantly aggravated due to the geology of the site (valley effects).

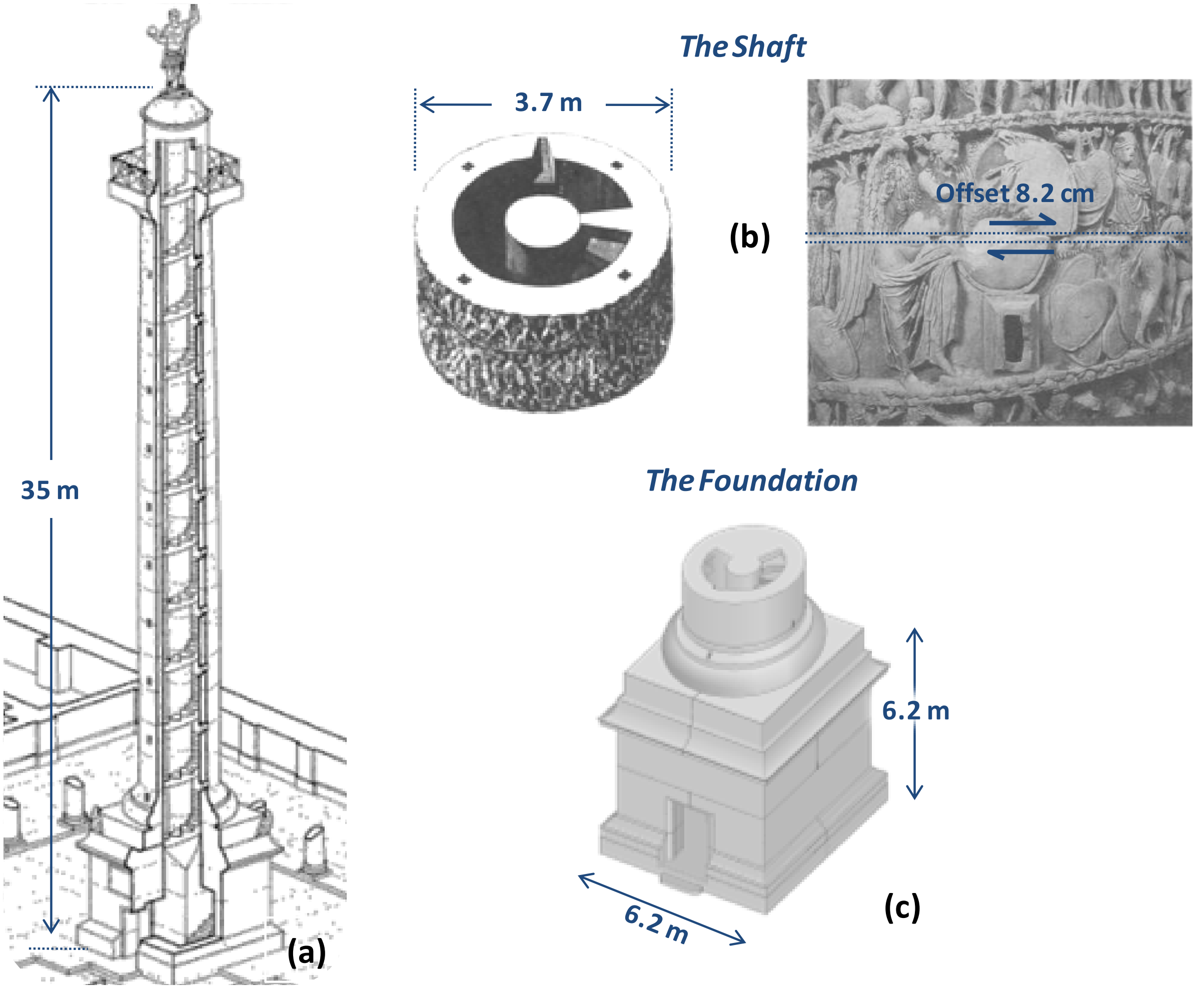

Figure 2: Triumph columns: (a) typical geometry, shown indicatively for the Column of Trajan, consisting of the pedestal base, the shaft and the capital; (b) geometry of the marble drums comprising the shaft and typical damage pattern, which involves sliding between the drums; (c) the pedestal - foundation.

Soil Classification Scheme

Leaving aside topography effects, this study focuses on the role of soft soil considering a qualitatively similar, yet simplified and at the same time more generalized problem. A single column is considered having the geometric and physical characteristics of the Marcus Aurelious Column (**Fig. 2**). It is founded on top of four idealised soil profiles with very different strength and impedance characteristics. As shown in **Fig. 3**, the assumed soil profiles are very simplified versions of the much more complex reality of actual sites and were selected in such way so as to better illustrate the effect of soft soil on the response of the soil–monument system. The idealized profiles address the case of a very deep soil deposit (as happens to be the deposit beneath the Marcus Aurelious Column) in comparison to a shallow soil layer (as is the case for the Trajan Column). More specifically, the analysis has considered:

- Two homogenous clayey soil profiles (designated as "Profile A" and "Profile B") of 60 m depth with the "soft" one having about 4 times lower strength and stiffness than the "stiff" one.
- Two layered profiles ("Profile C" and "Profile D"), where a "soft" or "stiff" 20 m deep clayey soil layer, is underlain by a rock formation.

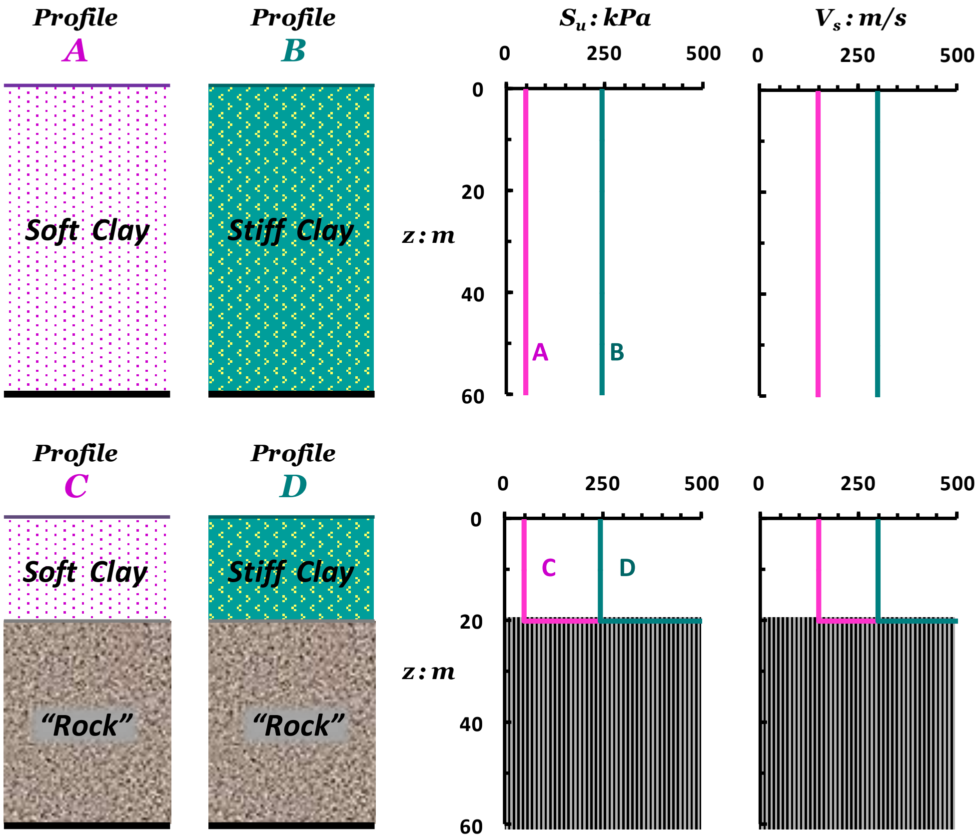

Figure 3: Strength and impendency characteristics of the 4 soil profiles used in the analysis.

Methodology

The problem was analyzed through Finite Element (FE) analyses implemented within the ABAQUS Code. First, a more comprehensive 3-D model of the column was built (**Fig. 4a**), which incorporates the detailed geometry of the column shaft, and more importantly, it accounts for the interface behaviour between the marble drums, allowing for sliding and uplifting to take place through appropriate interface elements. However, due to the increased number of degrees of freedom required to model the 3-D geometry and the additional complexity arising from the interfaces, this model was found to be too time consuming to implement in dynamic analyses involving soil.

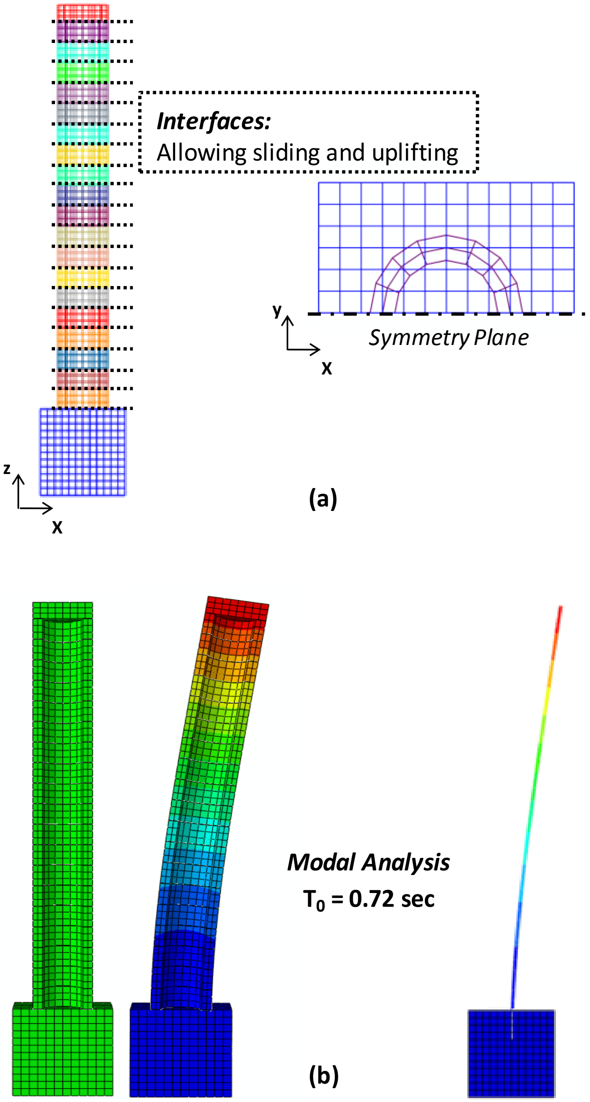

Figure 4: Finite Element modelling of the column: (a) detailed 3-D model; (b) calculation of the dominant period through modal analysis and definition of an "equivalent" 2-D model.

Hence, use of a more effective simplified model was deemed necessary. An equivalent 2-D oscillator was determined based on the requirement of having the same elastic dynamic properties with the more realistic 3-D model. The dynamic similitude between the two oscillators was achieved by demanding the same natural vibration period, calculated by modal analysis (**Fig. 4b**). The equivalent 2-D column has the same mass, slenderness and natural frequency with the 3-D one (f_0 = 1.4 Hz). However, the reader should bear in mind an important and unavoidable drawback, which arises from the inability of the 2-D model, where the shaft is modelled by a beam, to simulate the interface behaviour between the marble blocks. Hence, the analysis addresses the mode of response where the column is subjected to rocking motion as an indiscrete body, presumably standing for the case that the marble blocks are connected, and ignores the second type of failure, which involves sliding between the different marble drums.

The 2-D FE model of the system, incorporating both the column and the soil deposit, is shown in **Fig. 5**. The soil is modelled with nonlinear 4-noded continuum elements. The same type of elements, but with linear elastic behaviour, were utilized for the foundation–pedestal. Linear beam elements of appropriate section and stiffness were used for the shaft and the capital. The soil–pedestal interface was modelled using special interface elements, which allow the column to slide and detach from the supporting soil.

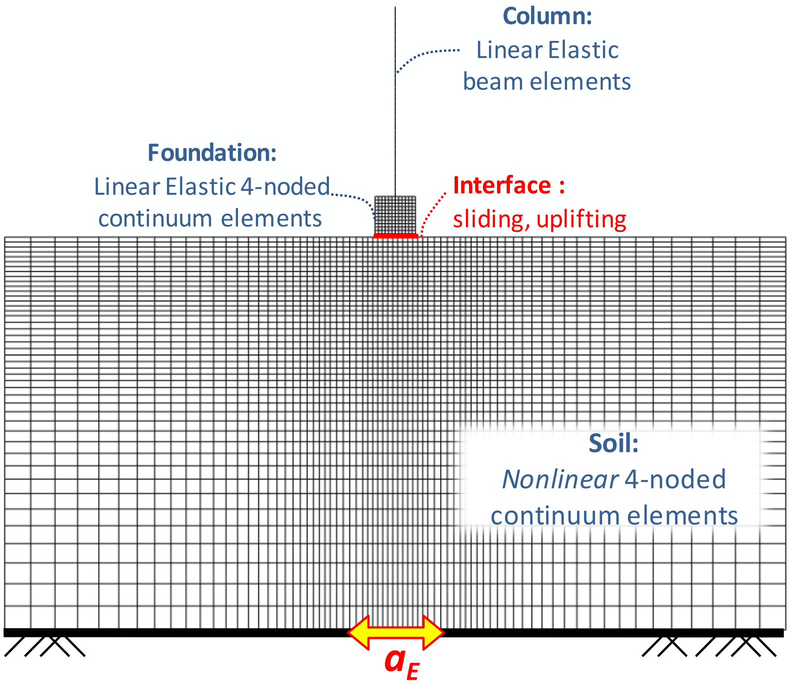

Figure 5: Details of the Finite Element mesh used in the plane-strain dynamic analysis of the soil – column system.

Nonlinear soil behaviour was simulated making use of a kinematic hardening constitutive model with Von-Mises failure criterion, which has been validated by the comparison with centrifuge model tests by Anastasopoulos et al., (2010) and implemented in a variety of soil – structure interaction studies (e.g. Anastasopoulos et al., 2010; Gelagoti et al., 2012). A comprehensive dynamic time history analysis was conducted, wherein the base of each one of the four soil profiles was excited by an idealized Ricker pulse. The virtues of using this particular excitation pulse for investigation of the dynamic response of slender oscillators have been identified by Loli et al. (2015). Here, three Ricker wavelets were used with their intensity (acceleration amplitude) and frequency being parametrically varied: f_E = 1, 2 and 3 Hz (see their response spectra in **Fig. 6**) at acceleration amplitudes a_E = 0.1, 0.2, 0.4, 0.6, 0.8 and 1 g.

A set of 72 analyses (18 for each one of the four soil profiles) were carried out and the results regarding the dynamic response of the soil and the performance of the column are compiled in the following section.

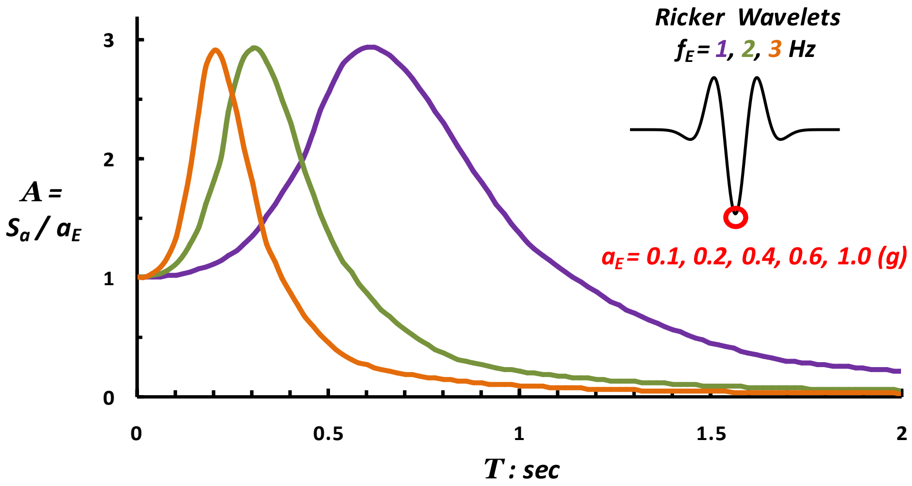

Figure 6: Ricker wavelets of 3 dominant frequencies (1, 2, and 3 Hz) with amplitudes ranging from 0.1 to 1.0 g were used in the dynamic analysis.

Presentation of Results

Due to paper size limitations, discussion of results of the entire suite of the FE analyses is herein based on synopsizing plots, avoiding the detailed presentation of time histories (acceleration and displacement) for individual seismic events.

Dynamic Response of the Soil Profile

Figures 7a and **7b** demonstrate the effect of soil stiffness on the magnitude of the seismic motion that reaches the ground surface for the deep and the shallow profiles, respectively. In both cases it appears that increasing the soil stiffness (i.e. increasing V_s) results in considerably more intense motions propagating to the surface. Thence, Profiles B and D transmit significantly higher inertial loads than their softer alternatives (A, C) for the whole range of the examined excitation magnitudes and for all three excitation frequencies. This is presumably due to the strongly nonlinear response of the latter, which leads to rapid degradation of the effective shear modulus and thereby to drastic attenuation of the motion through an effective rise of the dominant period and response hysteresis.

It is interesting to observe that in the case of stiff layered sites (**Fig. 7b**) larger ground surface accelerations occur with increasing the frequency of the excitation pulse (maximum response for excitation with Ricker-3Hz) and the response weakens as the excitation frequency reduces. Exactly the opposite is the case for the more flexible homogenous sites.

If the soil material was perfectly elastic, amplification of an excitation of particular frequency would be independent of the incident-wave amplitude and related only to the impedance of the soil deposit. However, in view of the actually nonlinear hysteretic response, material damping plays a dominant role and hence the response becomes dependent on the strain amplitude and consequently reduces with increasing excitation magnitude. This is clearly illustrated in **Figure 8**, where the amplification ratio (a_{ff}/a_E) is shown to consistently drop with increasing a_E. Furthermore, it is important to observe that material nonlinearity may even cause attenuation of the input motion ($a_{ff}/a_E < 1$) which presumably happens at lower a_E values in the cases of softer soils (profiles A and C). The extremely soft soil profile A causes attenuation of the input motion for bedrock accelerations greater than only 0.1 g and may even reduce the seismic input by as much as 50% for a_E > 0.2 g. Much larger accelerations are required to cause attenuation response in the stiffer soil sites. Note that these results are in qualitative agreement with the results produced by Idriss (1990) in his pioneering study of 1-D wave propagation on soft soil sites.

Additionally, it is essential to note that having a finite soil strength sets a clear margin on the maximum value of the transmitted acceleration amplitude in such way that the greatest inertial load applied instantaneously at any soil element cannot exceed its shear strength so that equilibrium is maintained (Newton's Law). This mechanism is very important for the two soft soil sites, where the behaviour appears to be controlled by the low shear strength and results in the plateau (practically horizontal curve) of the a_{ff} variation with excitation magnitude (**Figure 4.7**).

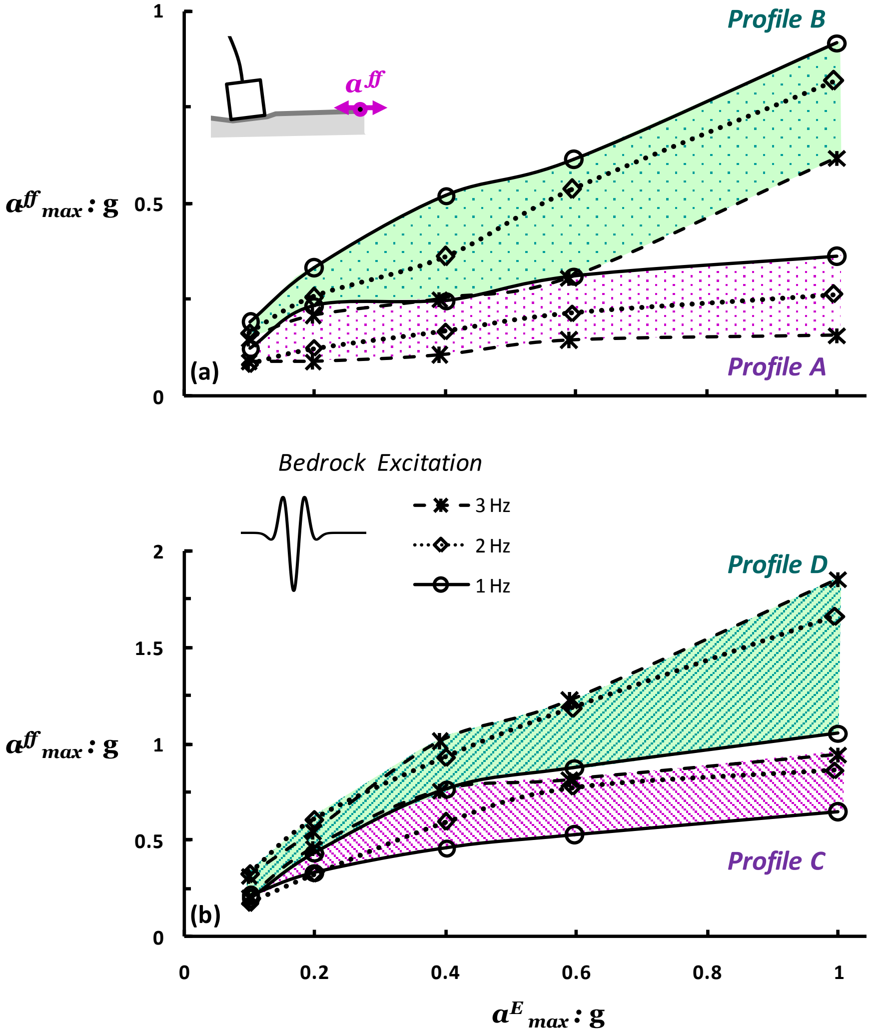

Figure 7: Summary of the dynamic response of the soil deposit for the entire set of bedrock excitations with Ricker pulses: peak surface acceleration, in free field conditions, with respect to the maximum acceleration input at the model base for (a) the two homogenous soil profiles A and B, and (b) the layered soil profiles C and D.

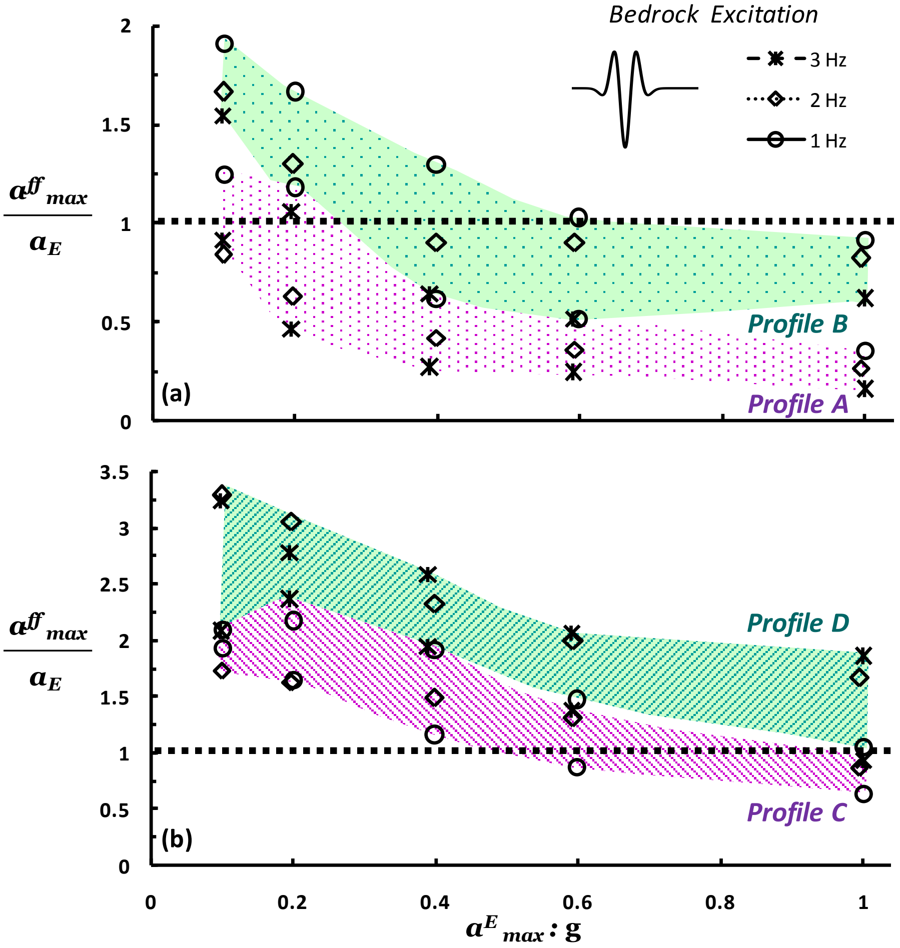

Figure 8: Amplification vs. attenuation response, expressed by the ratio of the maximum free field surface acceleration to the maximum acceleration at the model base, with respect to the excitation intensity, namely peak acceleration, for (a) the two homogenous soil profiles A and B, and (b) the two layered soil profiles C and D.

Summary and Conclusions

Triumph columns are often founded on very soft soil deposits or upon the debris of ancient cities in which case their seismic response may be considerably affected by soil behaviour. The role of soil in herein investigated in view of the performance of a simplified, equivalent structure assumed to stand on top of four idealized soil profiles with strikingly different stiffness characteristics. Results from a series of numerical analyses using nonlinear finite elements have been presented leading to the following conclusions:

1) Strongly nonlinear soil response often results in a drastic attenuation of the seismic motion propagating to the ground surface. In fact, the extremely soft/deep soil profile “A” was found to cause attenuation of the input motion for bedrock accelerations greater than only 0.1 g reaching attenuation factors as low as 0.5 for a_E > 0.2 g.

2) Nonlinear response at the soil – foundation interface effectively limits inertia forces transmitted to the column cutting-off accelerations experienced at the capital. This result is in agreement with numerical and experimental findings manifesting the virtues of rocking isolation (Anastasopoulos et al., 2010; 2013).

3) Interestingly, nonlinear foundation response generally leads to reduced maximum drift loads suffered at the capital. Counterintuitive as it may be, this result is in agreement with results from centrifuge model tests investigating the response of concrete structures (Loli et al., 2014).

4) On the other hand, there is a well known yet unavoidable price to pay: increased permanent deformations, namely settlements and rotations of the foundation. Especially settlements are an important consideration. As a result of the transient mobilization of bearing capacity failure mechanisms, settlement of the pedestal on soft soil can substantially exceed estimates for stiff soil.

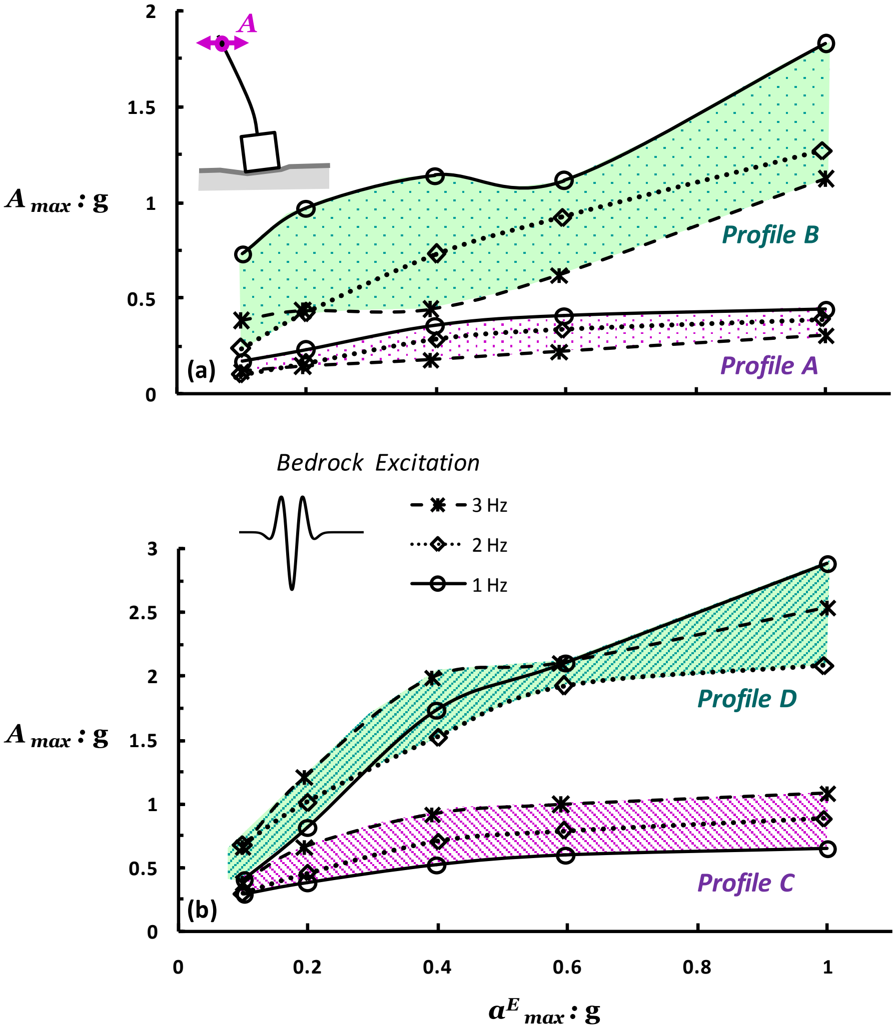

Figure 9: Summary of the dynamic response of the column: maximum acceleration experienced at the capital of the column with respect to the maximum acceleration input at the model base for the four different site profiles.

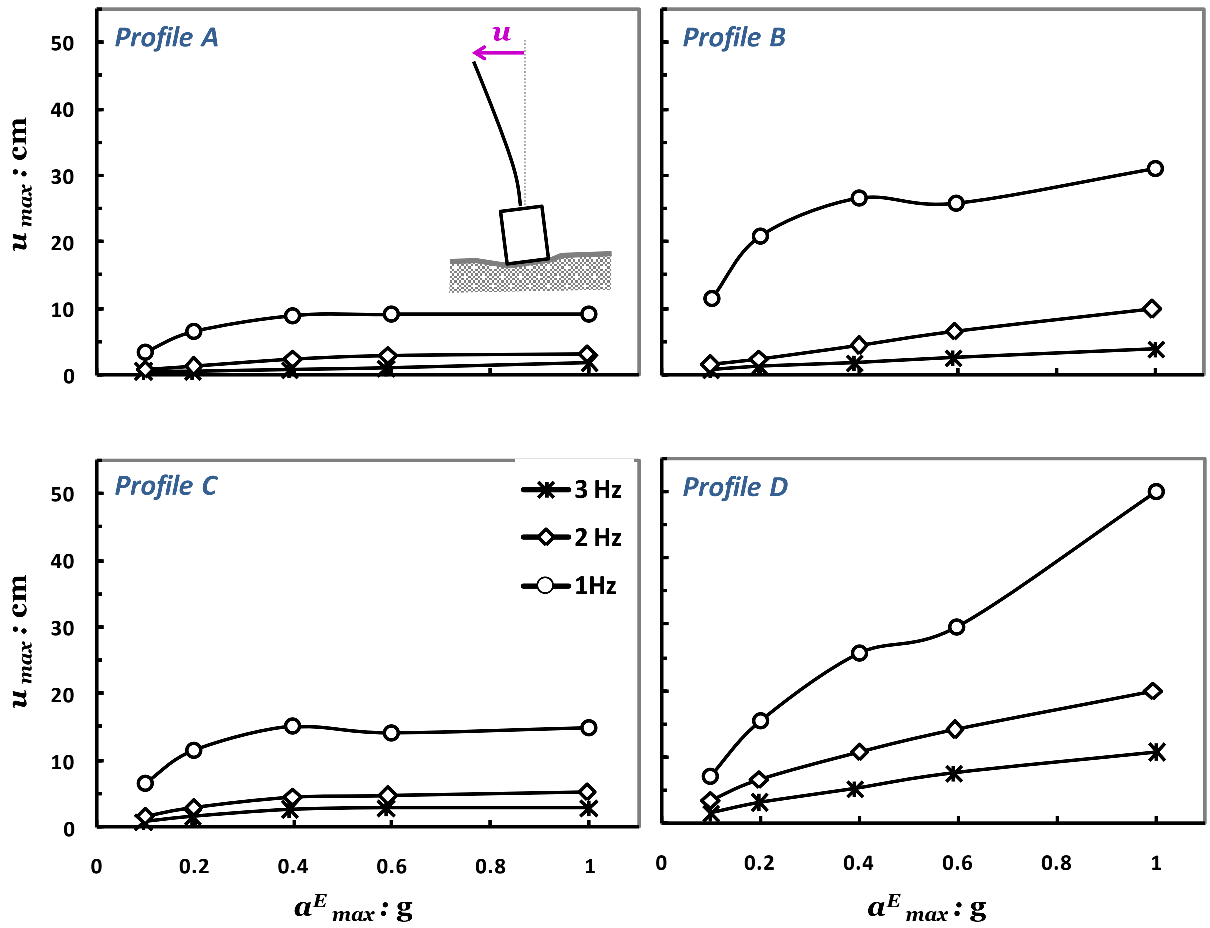

Figure 10: Synopsis of the column performance in terms of drift (u): maximum drift experienced at the capital with respect to peak input acceleration the whole range of Ricker excitations examined and the four different soil profiles.

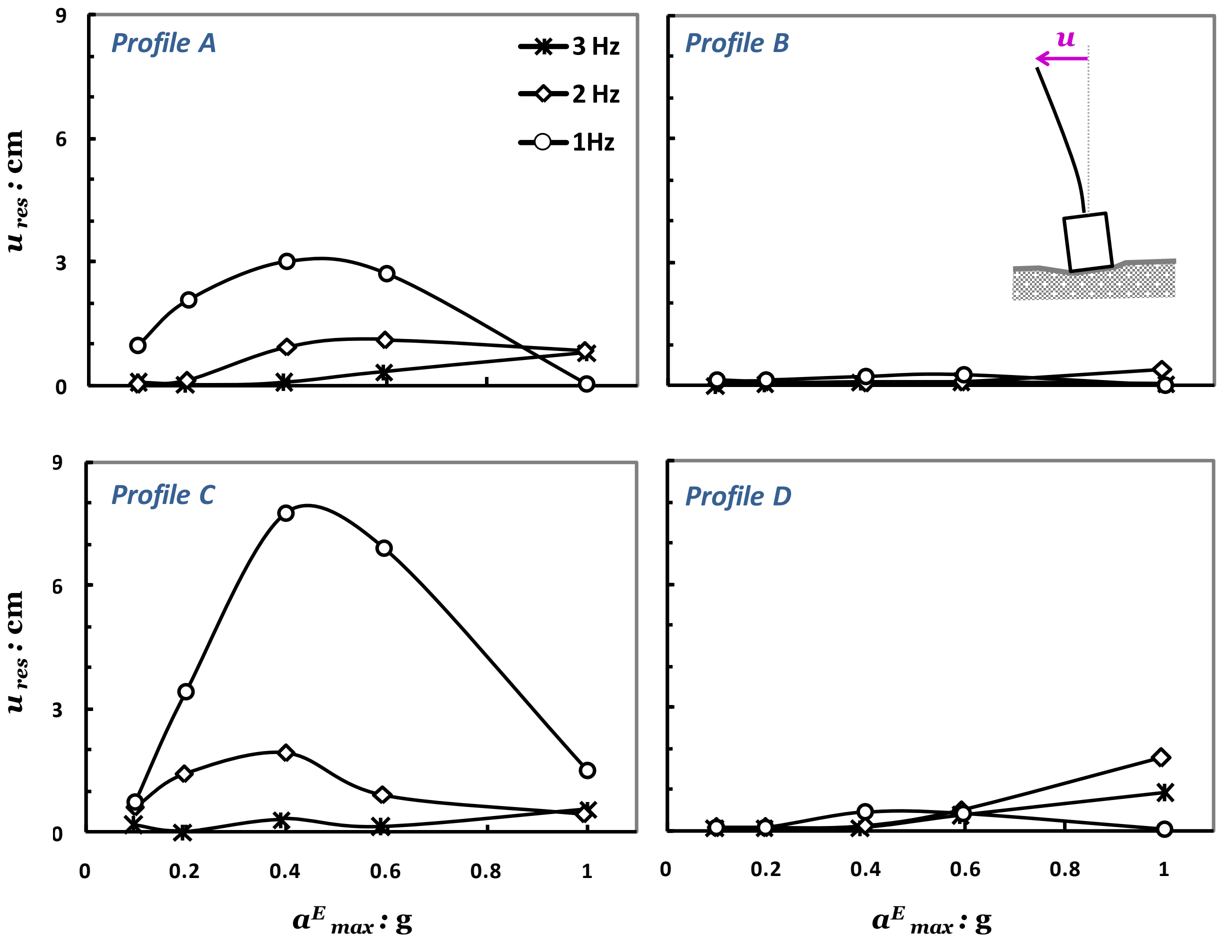

Figure 11: Residual drift of the column capital with respect to the excitation magnitude for the whole range of Ricker excitations examined and for the four soil profiles.

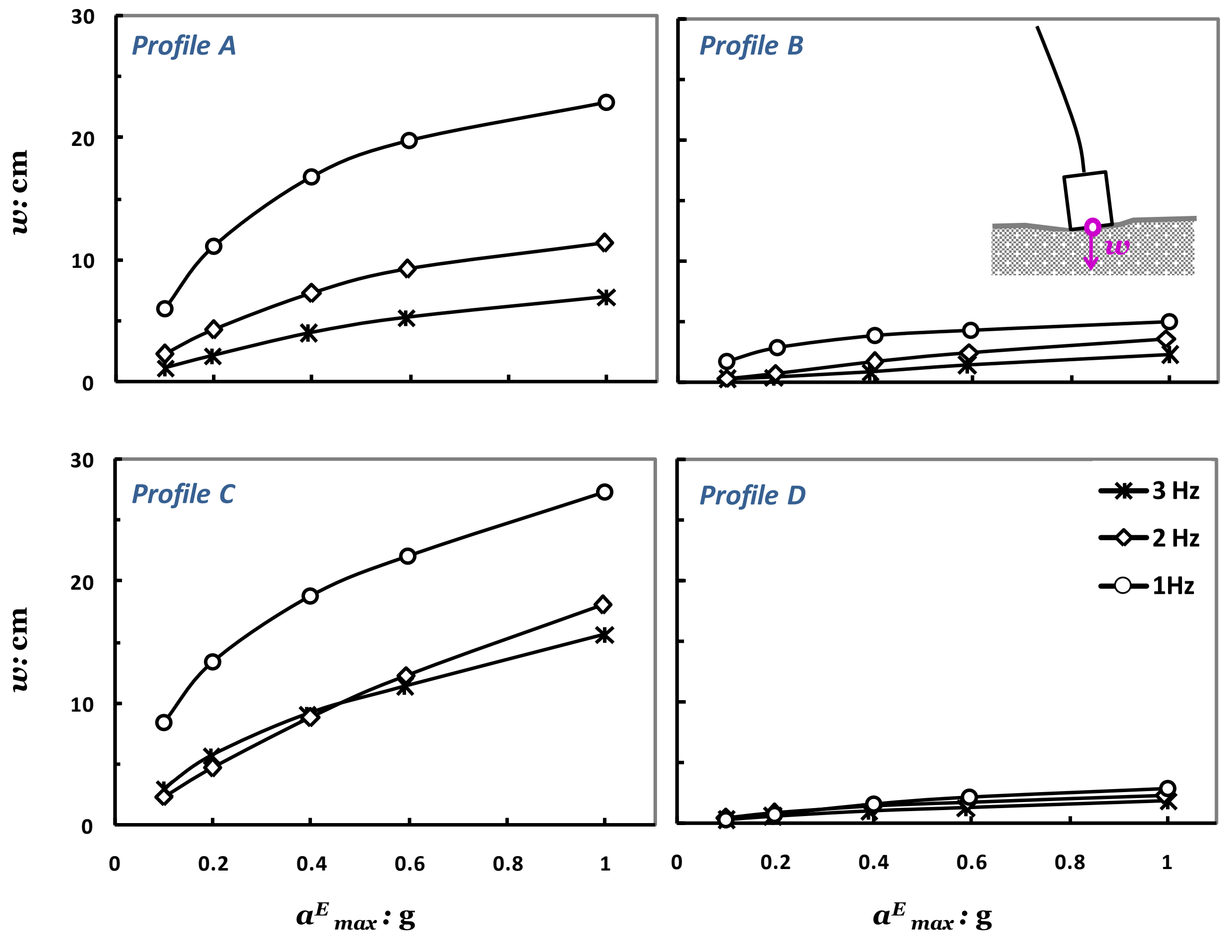

Figure 12: Synopsis of settlement response: column settlement with respect to the excitation magnitude for the whole range of Ricker excitations examined and for the four soil profiles.

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